EDITORS: Rita Borgo, rita.borgo@kcl.ac.uk
Kelly Gaither, kelly@tacc.utexas.edu

DEPARTMENT: VISUALIZATION CORNER

Scientific Visualization: Art, Nature, and Vocabulary

Francesca Samsel and Gregory Abram, *University of Texas at Austin, Austin, TX, 78757, USA*

Scientists increasingly rely on visualizations to interpret complex, multivariate, time-dependent 3-D datasets. However, standard visualization techniques often produce cluttered and difficult-to-interpret results. In this work, we explore an expanded visual design vocabulary inspired by patterns and forms in nature, aiming to represent complexity more harmoniously. We present initial experiments comparing this nature-inspired approach to conventional visualization defaults and demonstrate how the expanded vocabulary can improve clarity and information density in scientific data representations.

Visualization is the process of conveying the information embedded in data by leveraging our innate capacity for visual perception and understanding. The vocabulary of visualization refers to the set of visual elements used to represent different aspects of information—for example, lines to indicate paths through space, glyphs to encode positional data, and surfaces or volumetric forms to depict space-filling functions. The grammar of visualization is the manner in which the vocabulary is combined to convey a whole as a collection of parts.[1,2,3] The key challenge is choosing and applying visual structures that both faithfully represent the data and support intuitive exploration.

The basic vocabulary of visualization is well known—color, points, lines and glyphs (or marks in 2-D) are used in both 2- and 3-D visualization.[1,4] Three-dimensional visualization introduces the use of surfaces and volumetric representations to represent functions over a spatial domain. In typical applications, this core vocabulary is extended through the use of visual attributes that modify these basic geometric forms—for example, line color or dashing to distinguish types of trajectories, and variations in glyph shape or color to encode different data variables. Such variation allows lines and glyphs to represent more complex and differentiated information.

The grammar of visualization arises from the manner in which we perceive the world around us. Spatial relationships are fundamental to us. In 2-D information visualization, we use position, length, and area in a sophisticated grammar of familiar forms such as graphs, scatter plots, bar, and pie charts. In 3-D, the grammar largely derives from 3-D geometry and the physics of light. The efficacy of the 3-D grammar lies in making use of human 3-D perception, so it is advanced by the development of techniques to closely adhere to reality, of natural, and man-made environments.

In this article, we consider the other aspects of the language—the vocabulary and the rules that lead to expressive and effective communication via the language. We return to the real world to further enhance our vocabulary by choosing textures, line forms, and color from nature rather than the limited abstract palettes provided by our present systems. We enhance our visualization capabilities by enabling our language to incorporate the complexity and beauty of the world around us.

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VISUAL VOCABULARIES

Scientists approach us with complex datasets that capture information they need to understand and communicate. These datasets often include many variables that evolve over time and are colocated in space, with each variable contributing meaningfully to the science question. There is a growing demand for 3-D visualizations that can represent these variables simultaneously without introducing ambiguity or visual clutter that might obscure their relationships and correlations.

Here we discuss an expanded visual language, the vocabulary of which includes the color palettes, shapes and forms used to represent data. In specific, we look at the attributes of nature's visual vocabulary and the potential benefits in representing scientific data visually. As much of the discussion uses vocabulary and concepts from the artistic community, Table 1 provides a few definitions. Being able to distinguish the visual elements representing different categories or scales of data is critical. Much of the research in visualization and cognition probes our ability to differentiate the visual vocabulary used to encode data. Color Theory and Design Principles address fundamental characteristics of design elements and their visual opposites such as linear and curvilinear. Identifying and employing the contrasting scales enables one to hone the visual differentiation and associations within the visualization.[5] Figure 2 illustrates basic design elements and principles applied to the creation of 2D glyphs. Figure 4 illustrates the process of extracting 2D glyph forms from a photo of flowers (see Table 1).

Representing Data

Typically, the visual vocabulary used to represent individual data elements (such as colormaps, line styles, shapes, and textures) are selected from a narrow set of defaults provided by visualization tools. These built-in options often reflect the limited esthetic and perceptual considerations of the tool developers rather than the full expressive potential of visual language. Although many of these encodings have been evaluated individually for perceptual effectiveness, there has been relatively little research on how they perform in combination.[7]

Nature offers a vast and largely untapped reservoir of visual forms (shapes, line types, and textures) that can be applied to data visualization. By drawing on these natural patterns, we can create representations that are more perceptually intuitive and visually distinct. This expanded design vocabulary enables scientists to encode complex information with greater clarity and nuance, enhancing both interoperability and insight.

Scientists often need to represent the interactions of dozens of variables, but perceptual research indicates that we can only differentiate four to six variables within one visualization. The fundamentals of perceptional distinction, colormaps, categorization, and domain norms have laid the ground work from which we will build.[1,2,3,6] The goal is to produce richer, more nuanced renderings of multivariate data that support both in-depth exploration and analysis by scientists, as well as effective communication with broader audiences.

Harmonious Complexity

Among the many possible approaches to visualizing complex data, we present one that draws on the inherent harmony of the natural world to inform visual vocabulary and applies principles from art and design to guide compositional grammar. In nature, we routinely encounter dense, dynamic scenes—such as shifting weather patterns or the coordinated motion of a flock

TABLE 1. Terminology.

Concept	Definition
Artistic Design Theory	The visual elements and guiding design principles, developed within the artistic community over the centuries, that are used to construct images.[1]
Design Elements	The visual building blocks used to construct images—lines, shapes, forms, colors and textures.
Design Principles	The characteristics and structured used in image composition, including harmony, unity, rhythm, and continuity.[4]
Composition	The structure underlying the organization of visual elements within the image.
Artistic Contrast Theory	The identification of contrasting visual elements such as linear and curvilinear.[4,5]
Associative Color	Hues we associate with specific objects or meanings, such as red for danger and green for good.
Visual Vocabulary	The full range of visual elements that can be used to construct data visualizations.

of birds—that we interpret with ease. For example, the gusts of wind, swirling debris, and darkening skies that precede a storm form a coherent visual narrative involving air, water, and earth. Inspired by such natural palettes and structures, we have found that visualizations grounded in these principles can accommodate complexity while maintaining clarity and legibility of individual elements. Figure 1 illustrates visualizations using current widely used colormaps with a set drawn from a natural setting (cloud photo, center).

Creating visualizations that integrate multiple variables or datasets into a single image is inherently challenging. Selecting encodings that do not interfere with one another requires design expertise. Even trained designers may struggle with this task. Artists are often able to produce visually complex yet clear images by deliberately controlling composition (guiding attention, highlighting relationships, and establishing visual hierarchies). In data visualization, particularly for time-varying data, the composition is largely dictated by the data itself, limiting such control. As a result, even skilled practitioners may find it difficult to maintain clarity in complex, data-driven visualizations.

Artistic Contrast Theory

Artists create images, direct attention, create hierarchies, and organize content by controlling the type and amounts of contrast within an image. Visualizations require the same attention. Established artistic contrast theory in both color and form contains specific guidelines. For color, these contrast principles are well established—hue, saturation, and value or luminance and the seven types of color contrast.[5]

Applying artistic color contrast theory, in contrast to common default colormaps, is illustrated in Figure 1, which shows a visualization requiring three colocated data variables. The visualization on the left uses the three common colormaps—rainbow, heatmap, and cool–warm. The middle section shows two colormaps built from a photo of clouds. The figure on the right uses the cloud image palette on the same three variables but produces a much clearer image because within the palette of the cloud there is a range of harmonious hues from which to construct a palette.

Figure 1 shows two visualizations of data from a wildfire simulation. On the left, a standard colormap is used to show velocity along the streamlines, and uses arbitrary colors and transfer functions to represent other aspects of the data. On the right, the principles of artistic color theory are used to extracting detail by lowering overall contrast, employing muted tones, and providing contrast with the saturated section of the palette. The hues for the volumetric representation of fire are drawn for the cloud imagery in the center of the figure demonstrating nature's ability to illustrate harmonious palettes able to provide enough contrast to reveal the structures within the visualization.

Shape and form have similar contrast categories. Artistic design theory and design principles identify key properties that create contrast by their presence or absence.[4] A complete discussion is beyond the scope of this article, but examples of key types of contrast are illustrated in Figure 2. These include linear and curvilinear forms, open versus closed, rhythmic patterns, and symmetry versus asymmetry. These principles apply to line as well as 2-D and 3-D glyph design. Previous research on line and glyph forms highlights profile complexity and detail levels that both play a significant role in perceptual differentiation.[11,12] Figure 3 shows three visualizations with a range of line types drawn from artistic design theory principles. On the left, the green and black lines are presented using line types with a complex profile, though light in weight.

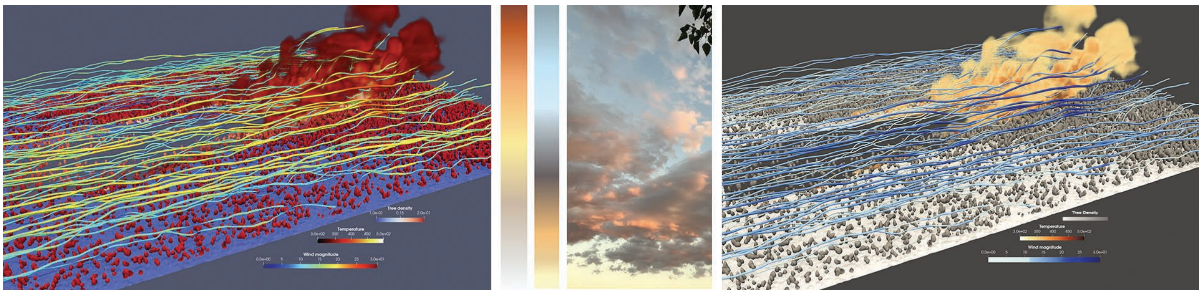

FIGURE 1. Fire simulation data including wind direction and water vapor levels, tree density and fire. Left: the three most common colormaps applied to the three variables. Middle: a photograph of a cloud and two colormaps created using the palette of the photograph. Right: the same data as on the left but colored with colormaps drawn from the cloud photo palette.

In the center, the white line is presented using a line type built using open shapes, while the muted yellow lines are comprised of organic curvilinear forms. On the right there are five distinct line types in use with an organic circular representing the water flow in white.

Previous additions to expanding the range of glyphs have relied on geometric distortions of a primitive form, or forms morphing from one form to another.[10] Nature provides a wealth of shapes and forms that could be adopted as glyphs, either abstracted or referential, as in chartography. Figure 3 shows visualizations incorporating three glyphs abstracted from natural forms. Two linear glyphs which imply rock forms and vary by the aspect ratio of the shape and density of the texture. The third is a flat semicurved triangular form, organic, implying a leaf form in the wind.

Expanding the vocabulary of lines, for which there is not much literature,[11] provides an opportunity to add another dimension of data. Generally, color is used to represent either categorical or scalar data on a line.

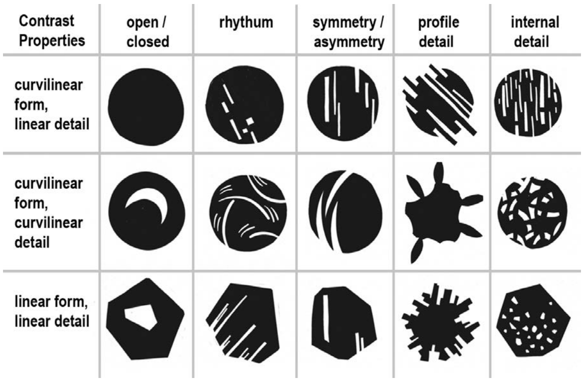

FIGURE 2. Examples of design principles, illustrated—linear, curvilinear, open versus closed—applied to 2-D glyph ideation.

An expanded selection of line types enables the line type to carry categorical data while the color carries scalar data. This is illustrated in contributions from Figure 3 showing five water currents in the Gulf of Mexico. The line pattern indicates the current's point of origin, enabling the colormaps to represent the temperature of the water.

Figure 5 illustrates the extraction of color sets, colormaps, lines, and glyphs from a series of rock face images. While the sources are similar, the range of color palettes, lines, and glyphs that can be extracted are broad. Tapping nature's visual richness through artistic practice not only expands our ability to encode more dimensions of a data set but also to do it using associative representations, allowing us to create more meaningful visualizations for the broader public.

Nature's Visual Language

Nature builds complex scenes that present a large variety of shapes, textures, and colors, providing information we have evolved to decode in order to survive. Shape and color enable us to identify the type of trees, helping us to know whether it has fruit, is poisonous, animals that might be present, and whether they are good for shelter construction. We know that our visual systems can dissect large volumes of complex intertwined information. What are the visual principles nature follows that enable it to present this level of detail within such visual complexity, enabling us to intuitively grasp its meaning?

Visual harmony is often thought to be in the eyes of the beholder, but actually visual harmony (like musical harmony) contains underlying principles that guide composition and image construction.[7,8,9] An orchestra includes many instruments, all generating distinct sounds, in a range of volumes and of specific notes

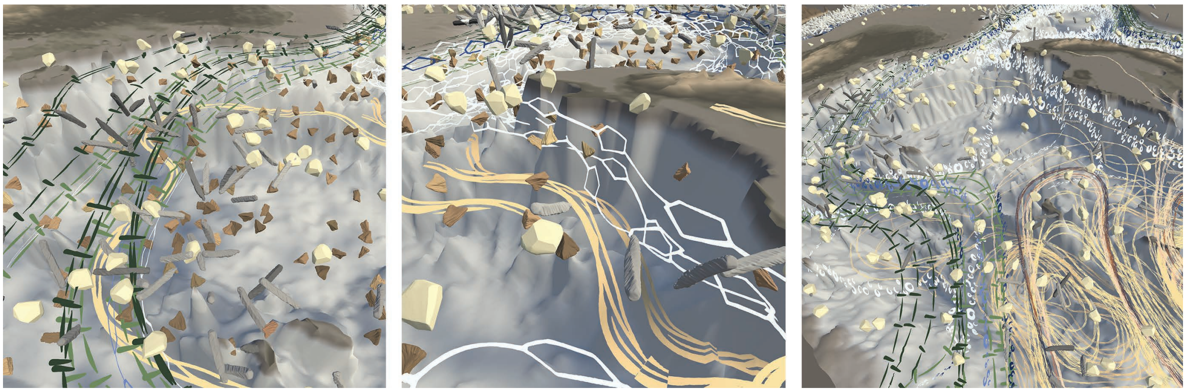

FIGURE 3. Visualization with lines and glyphs drawn from nature and selected for their contrasting design principles. Visualization data: MPAS-Ocean, LANL.

and tempos. In visualizations, the colors, surfaces, lines, and shapes are the instruments that need to be balanced within the framework of the data—the score, guided by design principles—musical theory, or as we outline next, the grammar.

Through evolution, humans have developed the ability to interpret visual cues in nature. Our survival depends on our ability to parse complex visual scenes in our environment. This raises a compelling question. Can nature's visual vocabulary be extracted to create the shapes, forms, and colors that when applied to data clearly convey the complexity within multivariate data?

Nature offers a vast and varied source of inspiration through its forms, colors, and textures. Although it remains an ambitious goal, mapping visual characteristics of natural forms to preattentive perceptual processes could yield powerful new tools for scientific visualization

CREATING PALETTES

Design practice offers a roadmap for extracting and abstracting natural colors and forms. Here we present examples of that process along with the results applied to data.

As shown in Figure 5, color, line, and shape can be extracted from natural scenes. Visually distinct sets can be built using artistic design principles. There are additional guidelines from the design community that reduce the interference *between* colors and symbols as well as enable discriminatory contrast between elements. Our prior work in color[8] focused on providing more detail and clarity in visualizations of data have shown us that design principles are useful and effective tools; however, when there are complex visualizations, they require an experienced designer. To our surprise, when we turned to natural imagery to extract palettes for visualization, the results were much clearer than when we relied solely on artistic color contrast theory, which has a 500-year history guiding artists. Our hypothesis is that we can extract lines, shapes, and textures from nature producing similar results.

An example of extracting glyphs is seen in Figure 4. From left to right, the figure illustrates the stages of abstraction to arrive at simple forms. Figure 5 illustrates color palettes and lines extracted from a series of photographs of rock formations. The hues can be used as discrete hues that will create a harmonious set, or they can be organized by luminance to create colormaps. To the right of each photograph is a line abstracted from the patterns in the rock. On the right

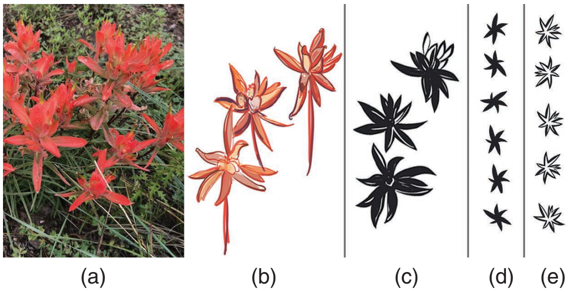

FIGURE 4. A diagram illustrating the process of glyphs and lines can be drawn from imagery. A. The photograph used as a source for the illustrations. B. A colored drawing from the photograph. C. A black and white graphic from the colored drawing. D. Shapes abstracted from the black and white drawing. E. An "open shape" variation.

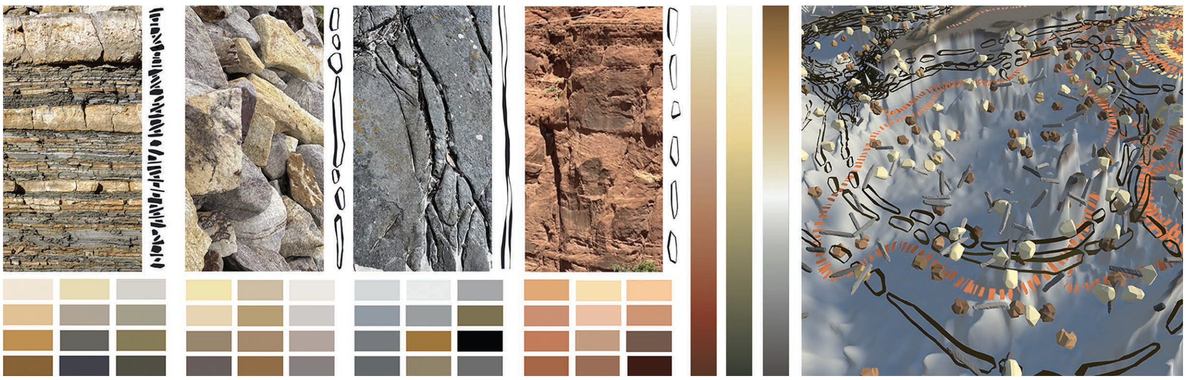

FIGURE 5. Images of four rock faces with line textures on the right of each and extracted discrete palettes below. On the right are three colormaps made from the discrete palettes and a visualization using the palettes and lines extracted from the rock imagery. Visualization data: MPAS-Ocean, LANL.

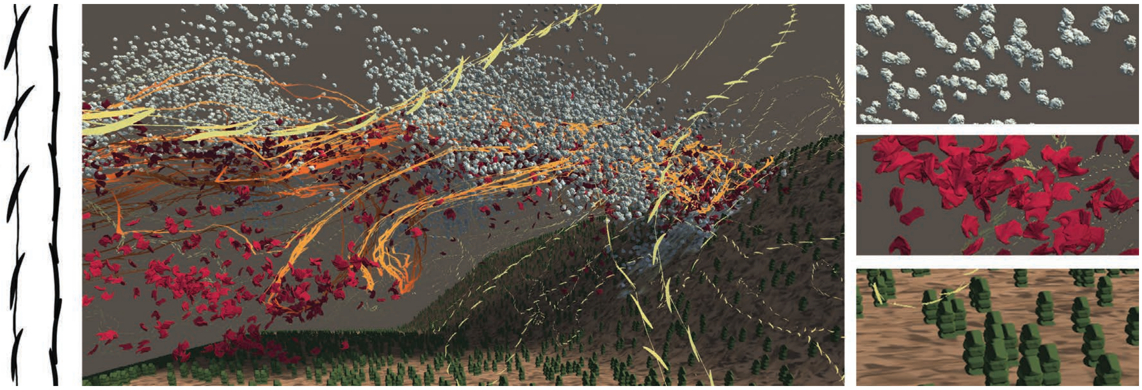

FIGURE 6. Fire simulation encoded with associative colors, glyphs, and lines. On the left are lines which are encoding two different wind categories. On the right are the three glyph categories: smoke, fire, and tree cover density. Data: HiGrad Wildfire Simulation, R. Linn, LANL.

is a visualization applying colormaps created from the hues extracted from the rock and lines applied to 3-D data.

In Figure 6, palette elements are selected for their association with the variables represented: wind, the fire path, the fire volume, and the tree cover density. The lines selected are curved and fluid with forms reflecting flames defining their character. Geometric abstractions of a tree represents the tree density. The volumetric data of the fire and smoke is sampled density and represented by curved flame-like forms, and puffy white forms, respectively.

CONCLUSION

This work advocates for expanding the visual vocabulary and grammatical principles that guide scientific visualization. Drawing inspiration from nature and integrating theories from art and design, we propose a foundation for developing a more expressive visual language. Design principles are guidelines for organizing imagery that serve as a grammatical structure for selecting visual vocabulary and composing coherent, meaningful representations.

Establishing this visual language is a significant undertaking. Once foundational vocabulary and grammar are defined, they must undergo extensive iterative testing across multiple contexts. Progress in four areas must proceed in tandem: clarifying the goals and evaluation criteria of visualization, identifying the needs of the scientific community, refining the visual vocabulary, and articulating grammatical guidelines. Dialogue between these areas is essential.

This approach mirrors artistic practice, where creation and evaluation are interwoven. As we develop this new visual language, insights from perception and cognition research, as well as close collaboration with domain scientists, will be indispensable.

While the examples presented here draw from nature, many other avenues remain open for exploration, each offering the potential to enrich the visual vocabulary and convey complexity more effectively through subtle, precise, and compelling means. We envision the development of distinct visual structures and dialects, incorporating color, line, glyphs, and texture, all thoughtfully adapted to different contexts and audiences. This marks a new chapter in this community's sustained effort to support scientists in uncovering insights from data and to foster broader public engagement through intuitive, richly layered representations of scientific knowledge.

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FRANCESCA SAMSEL is a research scientist in the Texas Advanced Computing Center, University of Texas at Austin, Austin, TX, 78757, USA. Contact her at fsamsel@tacc.utexas.edu.

GREGORY ABRAM is a research scientist in the Texas Advanced Computing Center, University of Texas at Austin, Austin, TX, 78757, USA. Contact him at gda@tacc.utexas.edu.
